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THE TAU AND BEYOND: FUTURE RESEARCH ON HEAVY LEPTONS*

MARTIN L. PERL
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

ABSTRACT: This paper outlines directions for future experimental research on the tau and tau neutrino. Present limits on the existence of heavier charged leptons are reviewed, with emphasis on the close-mass lepton pair concept.

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I. Introduction

In 1981, at the first *Physics In Collision Conference*, I reviewed the status of the tau and of the search for heavier leptons. Now, seven years later, I have the pleasure of presenting another such review.

Those seven years demonstrate the perversity of nature, or more precisely, demonstrate the obstinacy of nature with respect to the desires and expectations of the physicist. By 1981 the tau was established and the particle physicist looked forward to the discovery of more and heavier leptons. Two new electron-positron colliders PETRA and PEP were in operation, and the CERN $p\bar{p}$ collider was under construction. Surely we would find another charged sequential lepton, or an excited lepton, or a scalar lepton, as the mass search range extended to tens of GeV/c^2 from 4 GeV/c^2. That was not to be. (A small region of hope in this mass range is still offered by the close-mass lepton pair concept, Sec. IV.)

In the next seven years, new colliders are in operation or will begin operation: TRISTAN, the $p\bar{p}$ collider at Fermilab, the SLC, LEP and HERA. Again our hopes are high. The obstinacy of nature may continue—or there may be something new to find in the world of heavy leptons, but not what we expect. Therefore, one purpose of this review is to present a skeptical view of what we think we know about heavy charged leptons, using the tau as a model.

The history of the tau in the last seven years may provide another example of how nature does not always obey the wishes of the particle physicist. In 1981 we thought we understood the tau, although there were still some measurements to make. Seven years and many more measurements later (Fig. 1), I am not sure the tau is well-understood; there is the problem in the 1–charged particle decay modes, Sec. II.A.

The need to learn more about the tau is relevant to current discussions and proposals for very large luminosity e^+e^- colliders: Tau–Charm Factories,[1] B Factories and Z° Factories.

II. The Tau

A. *The Decay Mode Problem*

In the last year my colleagues and I have written three papers[2–3] covering various aspects of the tau decay mode problems, also a general review.[4] I'll summarize what we know, referring the reader to those papers[2–4] for the details—or it may be better not to read those papers, because they describe the failed attempts by many physicists to resolve the problem. A fresh view of the problem based only on a data summary may be best.

The average measured values of the inclusive branching fractions into 1, 3, 5 or 7–charged particles are[3,5,6]

$$\begin{aligned} B_1 &= (86.6 \pm 0.3)\% \\ B_3 &= (13.3 \pm 0.3)\% \\ B_5 &= (0.10 \pm 0.03)\% \\ B_7 &\geq 0.019\% \quad , \quad 90\% \text{ CL} \end{aligned} \tag{1}$$

The usual laws of the conservation of energy, charge, total angular momentum and lepton number require that B_1 be the sum of the decay fractions of the modes listed in Table 1. The modes listed in rows A–F have been measured in at least three different experiments. Some branching fractions are based on many measurements; for example, 10 for $B(\nu_\tau e^- \bar{\nu}_e)$ and 16 for $B(\nu_\tau \mu^- \bar{\nu}_\mu)$. Incidentally, B_1 is based on 11 measurements.

Since the energy available in τ decay is less than 1.78 GeV, we expect the branching fractions to be small for modes containing more than 3 π's or the relatively heavy η. As shown in rows H–L of Table I, this is the case. Published experiments have not been able to directly measure the branching fractions for these higher multiplicity or η-containing modes. The failure comes from one or more of the following problems: great difficulty in working backwards from detected photons to the original $\pi^0 \to \gamma + \gamma$ or $\eta \to \gamma + \gamma$ or $\eta \to \pi^0 + \pi^0 + \pi^0$, background and false photon signals, and insufficient statistics. Direct studies of the 1–charged particle modes in rows H–L yield only upper limits.

The sum of the branching fraction measurement and upper limits in Table 1 is $\lesssim (88.2 \pm 1.5)\%$, compatible with $B_1 = (86.6 \pm 0.3)\%$.

The 1–charged particle decay mode problem occurs when conventional theoretical considerations and other data are used to evaluate or set upper limits on the branching fractions

Table 1. Summary of direct measurements of branching fractions of 1-charged particle modes using only 1-charged particle decays.

Type of Information	Row	Decay Mode	Branching Fraction Fraction (%)
Measured in 1-charged particle decays	A	$\nu_\tau e^- \bar{\nu}_e$	17.6 ± 0.4
	B	$\nu_\tau \mu^- \bar{\nu}_\mu$	17.7 ± 0.4
	C	$\nu_\tau \pi^-$	10.8 ± 0.6
	D	$\nu_\tau \rho^-$	22.5 ± 0.9
	E	$\nu_\tau \pi^- 2\pi^0$	7.6 ± 0.8
	F	$\nu_\tau K^- n\pi^0 m K_L^0$ $n \geq 0,\ m \geq 0$	1.7 ± 0.4
Sums of rows A–F	G		$77.9 \pm\ 1.5$
Upper limit deduced or estimated in 1-charged particle decays	H	$\nu_\tau \pi^- 3\pi^0$	$<\ 2.5$
	I	$\nu_\tau \pi^- 4\pi^0 + \nu_\tau \pi^- 5\pi^0$	$\lesssim\ 4.$
	J	$\nu_\tau \eta$	$<\ 0.3$
	K	$\nu_\tau \eta n \pi^0$	$<\ 2.1$
	L	$\nu_\tau 2\eta$	$<\ 1.4$
Sum of rows H–L	M		$\lesssim 10.3$
Sum or rows A–F and H–L	N		$\lesssim 88.2 \pm 1.5$
1-charged particle topological B_1	0		86.6 ± 0.3

Table 2. Values and upper limits of branching fractions for 1-charged particle modes deduced from theory and other measurements. The sum does not include modes with $\nu_\tau \pi \eta n \pi^0$, $n > 2$.

Mode	Method	Value (%)	Upper Limit (%) 95% CL
$\nu_\tau \pi^- 3\pi^0$	c	1.0 ± 0.15	1.25
$\nu_\tau \pi^- 4\pi^0$	a		0.06
$\nu_\tau \pi^- 5\pi^0$	a		0.11
$\nu_\tau \pi^- \eta$	d		0.00
$\nu_\tau \pi^- \eta \pi^0$	c		0.24
$\nu_\tau \pi^- \eta 2\pi^0$	a		0.40
$\nu_\tau \pi^- \eta \eta n \pi^0$, $n \geq 0$	b		0.60
sum			2.7

a: use conservation of strong isospin

b: use $\eta \rightarrow \pi^+ + \pi^- + \pi^0$

c: use e^+e^- cross section and conserved vector current

d: $\nu_\tau \pi^- \eta$ requires a second class current amplitude

Table 3. Branching fractions for 1-charged particle decays.

Source of Information	Branching Fraction (%)
Sum of well measured modes from Table 1	77.9 ± 1.5
Sum of 95% CL upper limits from Table 2	≤ 2.7
Sum of above	$\leq 80.6 \pm 1.5$
Topological branching fraction B_1	86.6 ± 0.3

of the modes in rows H–L of Table 1. This is the work of Truong,[7] of Gilman and Rhie,[8] and of Gilman.[9] The upper limit for the sum of rows H–L reduces to 2.7%, Table 2. Then the sum of the individual, 1–charged particle, branching fraction measurement is $\leq (80.6 \pm 1.5)\%$ which does not agree with $B_1 = (86.6 \pm 0.3)\%$, Table 3. There is a missing 6%!

There are three general classes of possible errors in the measurements which might lead to the 6% discrepancy.

(i) The measured B_1 might be too large. This could happen if the detector simulation programs used to correct the observed B_1 and B_3 are wrong. However, this kind of error extending over most of the B_1 determinations has not been found. In an unpublished work, Dorfan[10] has shown that it is very difficult to reduce B_1 by more than one or two percent.

(ii) One or more of the measured individual branching fractions B_{1i} might be too large. Such a possibility is more likely than (i) because the ratio

$$B_{1i}\ (\text{observed})/B_{1i}\ (\text{corrected})$$

may be very small due to decay mode selection criteria and detector inefficiency. No one has been able to find the kind of error that would affect simultaneously most of the individual measurements making up an average value in Table 1. I'm still looking for such an error; I expect it to be cause of the discrepancy if the experiments are at fault.

(iii) Perhaps the error assigned to the 77.9% partial sum in Table 1 should be several times larger, destroying the significance of the 6% discrepancy. In two papers,[2,3] Hayes, Efron and I have examined this possibility. In the sets of measurements used for the average values of B_1, $B(\nu_\tau e^- \bar{\nu}_e)$, $B(\nu_\tau \mu^- \bar{\nu}_\mu)$, $B(\nu_\tau \pi^-)$ and $B(\nu_\tau \rho^-)$, there is no internal evidence that the errors should be enlarged. The errors associated with an individual measurement by the experimenters are either about right or too large, according to this internal evidence. There is, however, evidence for bias in the $B(\nu_\tau \rho^-)$ measurements and hints of bias in other measurements in the sense that the individual measurements cluster more about their central value than their individual errors would predict. We cannot tell if this bias has shifted the central value from the true value.

If the discrepancy of 6% is not due to measurement errors, there is something we do not understand about the 1–charged particle decay modes of the τ. I do not know of any hypothesis about something unknown in τ decays that fits all the τ data. There are several hypothesis[2,11] that don't fit the data.

I believe the most pressing future research on the τ is further study of the 1–charged particle decay mode problem. Unfortunately, I don't know what to study: the purely leptonic modes, the modes with many photons, or the observed decays that don't easily fit into the criteria for any accepted decay mode.

B. *Better Measurements of Conventional Properties of the Tau*

Our knowledge of the conventional properties of the τ is mostly based on measurements of modest precision, reinforced by our faith that the τ is simply a Dirac point particle which obeys the standard electroweak theory. All measurements in this section use the process

$$e^+ + e^- \to \tau^+ + \tau^- \tag{2}$$

with subsequent decays of the τ's.

1. *τ Mass:* The presently accepted mass

$$m_\tau = 1784 \pm 3 \ \ \mathrm{MeV/c^2} \tag{3}$$

is based mostly on 10 year old measurement.[12] A better measurement is needed to pursue m_{ν_τ}.

2. *τ Lifetime:* The average value of τ_τ from recent measurements[3] is

$$\tau_\tau = (3.03 \pm 0.09) \times 10^{13} \ \mathrm{s} \quad . \tag{4}$$

An improved measurement with improved control of systematic errors would be very useful because of the equalities:

$$\begin{aligned} \tau_\tau &= \tau_\mu \left(\frac{m_\mu}{m_\tau}\right)^5 B_e \\ \tau_\tau &= \tau_\mu \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B_\mu}{.973} \end{aligned} \quad . \tag{5}$$

At present τ_τ calculated from Eqs. 5 and the branching fractions in Table 1 is $(2.87 \pm 0.04) \times 10^{-13}$ s, which agrees with the measured τ_τ within 1.5 standard deviations.

3. *τ Spin:* The spin–1/2 value is required by the threshold behavior[13] of $\sigma(e^+e^- \to \tau^+\tau^-)$, by the high energy behavior of $d\sigma(e^+e^- \to \tau^+\tau^-)/d\cos\theta$ and $\sigma(e^+e^- \to \tau^+\tau^-)$, and by the measured value of $B(\nu_\tau\pi^-)$.[14,15] The threshold behavior measurement, Ref. 13, is ten years old. It would be nice to have a modern measurement.

4. *Electromagnetic Vertex:* For the past decade we have accepted the τ as a Dirac point particle with the τ–γ–τ vertex $\bar{v}_\tau \gamma u_\tau$. This leads to the formulae[16] for $d\sigma/d\Omega$ and the τ–τ spin correlations in

$$e^+ + e^- \rightarrow \gamma_{virtual} \rightarrow \tau^+ + \tau^- \quad . \tag{6}$$

We explore deviations from the Dirac point particle description using tests for a non-unit form factor, for an anomalous magnetic moment, and so forth. These are discussed in Sec. II.D.

5. *Weak Interaction Vertex: τ–W–ν_τ:* For the past decade we have taken the τ–W–ν_τ vertex as $\bar{v}_{\nu_\tau}\gamma(1-\gamma^5)u_\tau$, and simply tested how well V–A is obeyed. Burchat[17] gives an average value of 0.73 ± 0.07 for the Michel parameter, 0.75 is predicted for V–A. However, as Burchat[17] has emphasized, the most general τ–W–ν_τ vertex can have many forms if it is not restricted apriori to a mixture of V and A. She has discussed the measurements which are required to restrict the form of the vertex through experiments. There is a tremendous amount to be done, much of it beyond our present experimental power. Nelson[18] recently discussed exploration of the τ–W–ν_τ and τ–Z^0–τ vertices using τ production at the Z^0.

As measurements on τ decay continue and as we puzzle over the decay mode problem, it becomes important to the account of electroweak radiative corrections to these decays. This has been done by Marciano and Sirlin,[19] who point out interesting uses of the comparison of the calculated electroweak correction with measurement.

The τ–W–ν_τ vertex has also been studied[20] at the CERN $p\bar{p}$ collider using the τ production process

$$\bar{p} + p \rightarrow W^- + \ldots \tag{7a}$$

$$W^- \rightarrow \tau^- + \bar{\nu}_\tau \quad . \tag{7b}$$

They confirm the standard view of the τ with $g_\tau/g_e = 1.01 \pm 0.09 \pm 0.05$. As the number of observed W decays increases at the CERN and Fermilab colliders, the process in Eq. (7b) can be studied in detail.

6. *Weak Interaction Vertex: τ–Z^0–τ:* At present our knowledge,[17,21] of the τ–Z^0–τ vertex comes from the interference of

$$e^+ + e^- \rightarrow Z^0_{virtual} \rightarrow \tau^+ + \tau^- \tag{8}$$

with the $\gamma_{virtual}$ process in Eq. (6). The average measured asymmetry parameter[21] A_τ is $(-4.9 \pm 0.9)\%$ compared to the predicted -5.8%. At the Z^0

$$e^+ + e^- \rightarrow Z^0_{real} \rightarrow \tau^+ + \tau^- \tag{9}$$

will allow full studies[22,23] of the τ–Z^0–τ vertex, since 3% of the Z^0 decays will be τ pairs.

C. Tau Lepton Number Conservation

Table 4 gives present upper limits on τ decays which would violate τ lepton number conservation. The upper limits on branching fractions are in the range of 10^{-3} to 10^{-5}. There is no evidence for violation.

Discussions of τ conservation are sometimes related[24] to muon lepton number conservation. For example, $B(\mu^- \to e^-\gamma) < 2 \times 10^{-10}$ compared to $B(\tau^- \to e^-\gamma) < 2 \times 10^{-4}$. In lepton number nonconservation models where the same mechanism acts on the τ and the μ, one generally compares $(m_\tau/m_\mu)^n\, B_\tau$ with B_μ with $n \leq 4$. In such models the B_μ limit is more sensitive.

However, it is useful to take a broader view, and to search for τ lepton number violation as an independent phenomenon. At present the smallest upper limits in Table 4 are set by the number of observed τ decays, 10^5 or less. Observed τ decay samples of 10^7 per year will be obtained if very high luminosity e^+e^- colliders are built in the low or moderate energy range.

D. Deviations from a Dirac Point Particle

1. General Remarks: There are two ways to speculate how the τ might deviate from being a Dirac point particle. First, it might not be a point particle, but be extended or composite. Second, it might be a point particle but have unexpected properties: an anomalous magnet moment or a nonzero dipole moment. The two classes of speculations merge because experimental limits can often be applied to both classes. Also, the second class might be considered a subdivision of the first class in which the structure is too small to be directly detected.

Silverman and Shaw[25] have given the convenient formula for possible deviations in the $e^+ + e^- \to \tau^+ + \tau^-$ differential cross section.

$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi\alpha^2\beta}{3s}\left[G_0(s) + \frac{1}{2}(3\cos^2\theta - 1)G_2(s)\right] \tag{10a}$$

$$G_0(s) = F_1^2(1 + 2m_\tau^2/s) + 3F_1F_2 + F_2^2(s/8m_\tau^2 + 1) \tag{10b}$$

$$G_2(s) = \frac{1}{2}(1 - 4m_\tau^2/s)(F_1^2 - F_2^2 s/4m_\tau^2) \quad . \tag{10c}$$

This is in the barycentric system of total energy $\sqrt{s}$, β is the τ velocity in units of c, θ is the angle between the e^- and the τ^- momenta, and m_τ is the τ mass. For a point Dirac particle $F_1 = 1,\ F_2 = 0$.

Table 4. Upper limits on branching ratios for τ decay modes that would violate tau lepton number conservation. Limits at 90% confidence level. ℓ^- means e^- or μ^-.

Decay Mode	Upper Limit	Experimental Group	Reference
$\tau^- \to e^-e^+e^-$	3.8×10^{-5}	ARGUS	H. Albrecht *et al.*,
$e^-\mu^+\mu^-$	3.3×10^{-5}		Phys. Lett. **185B**, 228 (1987)
$\mu^-e^+e^-$	3.3×10^{-5}		
$\mu^-\mu^+\mu^-$	2.9×10^{-5}		
$\ell^-\ell^\mp\ell^\pm$	3.8×10^{-5}		
$e^-\pi^+\pi^-$	4.2×10^{-5}		
$\mu^-\pi^+\pi^-$	4.0×10^{-5}		
$e^-\rho^0$	3.9×10^{-5}		
$\mu^-\rho^0$	3.8×10^{-5}		
$\ell^\mp\pi^\pm\pi^-$	6.3×10^{-5}		
$e^-\pi^+K^-$	4.2×10^{-5}		
$\mu^-\pi^+K^-$	1.2×10^{-4}		
e^-K^{*0}	5.4×10^{-5}		
μ^-K^{*0}	5.9×10^{-5}		
$\ell^\mp\pi^\pm K^-$	1.2×10^{-4}		
$e^-\gamma$	2.0×10^{-4}	CRYSTAL BALL	S. Keh *et al.*, (1988)
$e^-\pi^0$	1.4×10^{-4}		DESY 88-065
$e^-\eta$	2.4×10^{-4}		SLAC-PUB 4634
			HEN-25
e^-K^0	1.3×10^{-3}	MARK II	K. G. Hayes *et al.*,
μ^-K^0	1.0×10^{-3}		Phys. Rev. **D25**, 2829 (1982)
$\mu^-\gamma$	5.5×10^{-4}		
$\mu^-\pi^0$	8.2×10^{-4}		
$e^-\pi^0$	2.1×10^{-4}		

2. Size of the τ: If the τ is to be tested for nonzero size or for being composite, it is customary to set $F_2 = 0$ and set

$$F_1^2 = 1 \pm \frac{s}{s - \Lambda_\pm^2} \quad . \tag{11}$$

Measurements of F_1 are then used to show[4] that $\Lambda_\pm$ is of the order of 200 GeV or more, and this in turn is interpreted to mean that the size of the τ is less than 10^{-16} cm. I don't like this way of measuring the deviation of the τ from a point particle because the form factor expression in Eq. (11) has limited meaning and the interpretation is nonrelativistic. I am looking into a way of measuring the deviation based on Ref. 26.

3. τ Magnetic Moment: As has been done for the e and μ, we would have to measure precisely the τ magnetic moment

$$\mu_\tau = \frac{g_\tau}{2} \frac{e\hbar}{2m_\tau c} \quad ; \tag{12}$$

sorting out the terms in the series[21]

$$(g_\tau - 2)/2 = a_\tau = a_{\tau 1}\left(\frac{\alpha}{\pi}\right) + a_{\tau 2}\left(\frac{\alpha}{\pi}\right)^2 + a_\tau^{weak} + \ldots \quad ,$$

but we don't have any idea how to test even for the first term in the series, expected to be $\frac{1}{2}(\alpha/\pi) \sim 10^{-13}$.

4. τ Electric Dipole Moment: Hoogeveen and Stodolsky[27] have proposed a test for a nonzero electric dipole moment. This test uses the process $e^+e^- \to Z^0 \to \tau^+\tau^-$.

E. The Concept of Lepton–Specific Forces and the Tau

Hawkins and I[26] have explored the limits imposed by published experiments on the existence of a force associated only with charged leptons. We use a model in which a neutral particle called λ couples to a charged lepton ℓ with a lepton number conserving interaction. Two examples of possible interactions are used: a pseudoscalar λ with pseudoscalar coupling $g_{\lambda\ell}\bar{v}_\ell\gamma^5 u_\ell$, and a vector λ with vector coupling $g_{\lambda\ell}\bar{v}_\ell\gamma u_\ell$. We define

$$\alpha_{\lambda\ell} = g_{\lambda\ell}^2/4\pi$$

and call the λ mass m_λ. This model provides a general way to compare the relative sensitivity of different methods of searching for new forces associated with charged leptons. Further motivation is given in Ref. 26. Existing measurements on quantities such as the e gyromagnetic ratio g_e and the cross section for $e^+e^- \to e^+e^-$ exclude large regions of $\alpha_{\lambda e} - m_\lambda$ space.[26]

If we take the λ to couple to the e and the τ, then the reaction

$$e^+ + e^- \to \tau^+ + \tau^- \tag{13}$$

will proceed through both diagrams in Fig. 2. Measurement at 29 GeV total energy of the cross section for the reaction in Eq. (13) agrees with calculations using only the virtual γ diagram. This gives the upper limits on

$$\alpha_{\lambda e\tau} = g_{\lambda e} g_{\lambda\mu}/4\pi$$

shown in Fig. 3.

If the λ couples only to the τ, there are two ways to search for the λ. One method involves once again $e^+e^- \to \tau^+\tau^-$. A deviation from the expected behavior of the cross section could be interpreted as the effect of a virtual λ at the τ–γ–τ vertex. The other method searches for the emission of a λ by a τ before the τ decays. This requires $m_\lambda < m_\tau$. I have not yet considered these methods quantitatively.

III. The Tau Neutrino

A. *Tau Neutrino Mass*

The smallest upper limit on $m_{\nu\tau}$ is

$$m_{\nu_\tau} \leq 35 \text{ MeV/c}^2 \quad , \quad 95\% \text{ CL}$$

from an experiment by the ARGUS collaboration[28] using the decay

$$\tau^- \to \nu_\tau + 3\pi^- + 2\pi^+ \tag{14}$$

In this method, the upper limit is set by finding decays in which the total mass of the five π's is close to m_τ. The precision which this method can achieve is being considered,[29] a ν_τ mass as small as several MeV/c might be detected. An alternative method[24,30] would use the decay

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \quad ,$$

comparing the maximum e^- energy with the energy of the τ just above the $e^+e^- \to \tau^+\tau^-$ threshold.

The technology of particle physics frustrates us, we don't know if several MeV/c^2 is a reasonable search range or still much too large for $m_{\nu\tau}$. For example, suppose there is substantial dark matter in the universe and the dark matter is the ν_τ, with a mass of several tens of eV/c^2. How can we measure that mass? A hope, but a waning hope, is that the ν_τ mixes with other neutrinos. The m_{ν_τ} might be determined through such mixing.

B. *Tau Neutrino Mixing*

It is an issue of faith as to whether neutrinos mix, or specifically whether ν_e and ν_τ or ν_μ and ν_τ mix. Two conditions have to be met: both neutrinos must have nonzero mass and lepton number conservation in the neutrinos must be violated. It would be wonderful if these conditions are met, but all we know at present is that there is no evidence for ν_τ mixing.

And so, as with the gyromagnetic ratio g_τ, our desire for knowledge about m_{ν_τ} far exceeds our technology.

C. *Interactions of the Tau Neutrino*

1. The ν_τ in τ Decay:

All we know about the dynamics of the ν_τ comes from the study of τ decays:

$$\tau^- \rightarrow \nu_\tau + \text{other particles} \quad .$$

It's spin[15] is 1/2. As discussed in Sec. II.B.5, its behavior agrees with V–A for the τ–W–ν_τ vertex. As we learn more about that vertex, we will see if our conventional views of the ν_τ are correct.

2. Interaction of the ν_τ with Hadrons: Two problems have prevented detection of the interaction of ν_τ's with hadrons. First, we don't know how to make a pure ν_τ beam. Second, it is difficult to detect a $\nu_\tau + N$ interaction in the presence of $\nu_e + N$ and $\nu_\mu + N$ interactions; N means nucleon or nucleus. Myatt[31] has given a general review.

The best way so far proposed for making a ν_τ beam is the sequence

$$p + N \rightarrow D_s + \ldots \tag{15a}$$

$$D_s \rightarrow \tau^- + \bar{\nu}_\tau \tag{15b}$$

$$\tau^- \rightarrow \nu_\tau + \ldots \quad . \tag{15c}$$

The ν_τ flux depends on the cross section for $\sigma(D_s)$ in Eq. (15a) and the decay branching fraction $B(D_s \rightarrow \tau\nu_\tau)$ in Eq. (15b); $\sigma(D_s)$ is of the order of μb's and $B(D_s \rightarrow \tau\nu_\tau)$ is estimated[31] at about 4%, but could be smaller. The $p + N$ interaction produces other charmed hadrons, such as D's and Λ_c, as well as π's and K's. Neutrinos from π and K decays can be suppressed by attenuating the π's and K's by interaction before decay, but the ν_e and ν_μ flux from D and Λ_c is still ten or more times larger than the ν_τ flux.

Several methods[31] have been proposed for detecting a $\nu_\tau + N$ interaction. One method would use a high resolution bubble chamber to directly see the decay of the τ produced via

$$\nu_\tau + N \rightarrow \tau^- \ldots \tag{16a}$$

$$\tau^- \rightarrow x^- + \ldots \tag{16b}$$

or

$$\tau^- \rightarrow x^- + x^+ + x^- + \ldots \quad . \tag{16c}$$

The decay of the τ to 3–charged particles, Eq. (16c), would be easiest to detect, but that is only 13% of τ decays. Other $\nu_\tau + N$ detection methods[31–34] use kinematic properties of τ decays which differentiate such events from $\nu_e + N$ or $\nu_\mu + N$ events.

There have not been any dedicated experiments looking for $\nu_\tau + N$ interactions, but a number of experiments on prompt neutrinos from a proton beam dump have searched for $\nu_\tau + N$ interactions. An example is M. Talebzadeh et al,[34] which reports the use of the BEBC bubble chamber at CERN in a $p + Cu$ beam dump experiment. They do not find $\nu_\tau + N$ events, and can only set an upper limit on the production of ν_τ's.

D. *Variations on the Tau Neutrino*

Our experimental ignorance about ν_τ allows us to speculate on variations from the conventional picture of a neutrino. For example, if $m_{\nu_\tau} > 0$, how stable is ν_τ against decay? We know from $e^+e^- \rightarrow \tau^+\tau^-$ events that the ν_τ decay length is larger than about 100 m, but that's all we know from direct experiments.

The tau decay problem, Sec.II.A, has also stimulated speculations about ν_τ. I tried a speculation[11] with a second massive ν_τ to explain the problem, it didn't work. Glashow[35] has suggested some models in which an unstable ν_τ would produce photons in its decay, confusing measurements of individual τ branching fractions.

IV. Limits on the Existence of Heavier Charged Leptons

A. *Present Limits*

This summary is limited to stable charged leptons (L^-) and sequential lepton pairs (L^-, L^0).

The lower limit on new stable charged leptons is set by experiments at TRISTAN:

$$m_- > 27.8 \text{ GeV}^2 \quad , \quad 95\% \text{ CL} \quad . \tag{17}$$

This limit includes single charged leptons and lepton pairs with $m_0 > m_-$.

Traditional sequential lepton pair searches with $m_0 < m_-$ have assumed

$$m_0 = 0$$

Recent sequential lepton pair searches have allowed the possibility.[38,39]

$$m_0 > 0 \tag{18a}$$

with $m_0 < m_-$ so that the decay

$$L^- \to L^0 + \text{ other particles} \tag{18b}$$

still occurs. It is convenient to define the mass difference

$$\delta = m_- - m_0 \quad . \tag{18c}$$

In heavy lepton searches using

$$\begin{aligned} &e^+ + e^- \to L^+ + L^- \quad , \\ &L^+ \to \bar{L}^0 + \text{ other particles} \quad , \\ &L^- \to L^0 + \text{ other particles} \quad , \end{aligned} \tag{19}$$

special methods must be used[39,40] when $\delta \lesssim 4$ GeV/c^2, because the detected energy—usually called visible energy—is relatively small. These special methods have so far only been applied to searches at 29 GeV total energy.[39,40]
Riles[41] has developed a different small–δ search method using the radiative process

$$e^+ + e^- \to L^+ + L^- + \gamma \quad .l$$

The small–δ problem also limits the significance of searches for heavy charged leptons $\bar{p}p$ colliders. These searches[42] use

$$\begin{aligned} &\bar{p} + p \to W^- + \text{ other particles} \quad , \\ &W^- \to L^- + \bar{L}^0 + \text{ other particles} \quad , \\ &L^- \to L^0 + \text{ other particles} \quad , \end{aligned} \tag{20}$$

and depend on a relatively large missing transverse momentum[43] in these events. Table 5 lists the published experiments on the existence of new heavy charged leptons, where $m_0 > 0$ has specifically been considered in the publication. In the case of the experiments at TRISTAN, AMY[36] and VENUS,[37] and the UA1 result,[42] I also note the lower limit on m_- when $m_0 = 0$. The excluded $\delta - m_-$ or $m_0 - m_-$ regions are shown in Figs. 4-7. The combined excluded $\delta - m_-$ region is given in Fig. 8.

Table 5. Publications on limits on new heavy lepton masses, m_- and m_0, when $m_0 \geq 0$.

Method	Lower limit on m_- (GeV/c^2) when $m_0 = 0$	Experiment	Figure	Reference
$e^+e^- \rightarrow L^+ + L^-$ at 29 GeV		Mark II	4	40
$e^+e^- \rightarrow L^+ + L^-$ at 29 GeV		TPC	5	44
$e^+e^- \rightarrow L^+ + L^-$ at 56 GeV	27.6 , 95% CL	AMY	6	36
$e^+e^- \rightarrow L^+ + L^-$ at 56 GeV	27.6 , 95% CL	VENUS	7	37
$\bar{p}p \rightarrow W^- + \ldots$ $W^- \rightarrow L^- + \bar{L}^0$	41. , 90% CL	UA1	8	42, 43

B. Future Searches for Charged Leptons

The μ mass is 200 times the e mass and the τ mass is 17 times the μ mass. If there is a heavier charged lepton, what is its mass compared to the τ mass?

Electron-positron colliders, operating or under construction, will allow searches up to 50 times the τ mass. In addition, W^- decay searches using the processes in Eq. (20) will be useful within this projected mass range. We look ahead to the following phases of the search:

(*i*) e^+e^- searches at $\sqrt{s} < m_{Z^0}$:
The task is to explore the m_δ space in Fig. 8 for small values of δ. TRISTAN will bear the burden, although further analysis of existing data from PETRA can help. TRISTAN will also be able to extend their search for stable charged leptons.

(*ii*) e^+e^- searches at $\sqrt{s} = m_{Z^0}$:
Finally, a complete exploration of the $m_- - \delta$ space for $m_- \leq 40$ GeV/c^2 can be made using Z^0 decays at the SLC and LEP. These are multiple signature for sequential lepton pair with $m_0 < m_-$: an increase in the Z^0 width from $Z^0 \rightarrow L^+L^-$, an increase in the Z^0 width from $Z^0 \rightarrow L^0\bar{L}^0$, and the decays $L^- \rightarrow L^0 +$ other particles. The search for a stable charged lepton will extend to $m_- \approx 45$ GeV/c^2.

(*iii*) Searches using W decays:
As the number of observed W decays increases substantially at the Fermilab and CERN $\bar{p}p$ colliders, the search using $W^- \rightarrow L^- + \bar{L}^0$ may extend into the m_- range of 60 to 70 GeV/c^2. However, the present L^- detection method using missing transverse momentum will require $\delta > 10$ to 20 GeV/c^2.

(*iv*) e^+e^- searches at $\sqrt{s} > m_{Z^0}$:

As the total energy of LEP extends toward 200 GeV, the traditional $e^+e^- \to L^+L^-$ search methods will reach the range of $m_- \sim 80$ GeV/c^2 for sequential charged leptons and single charged leptons. A thorough search of $\delta - m_-$ space will require attention to the small δ region. I am not aware of studies of how to explore the small δ region when m_- is so large.

I hope that Nature will be kind with the search methods just discussed, allowing us to find a new heavier lepton. If not, we shall have to wait for yet more powerful colliders to be built. Search methods using e^+e^- colliders are straightforward provided the luminosity is sufficient. There is disagreement as to whether pp colliders can be used to search for sequential charged leptons, once $m_- > m_W$.

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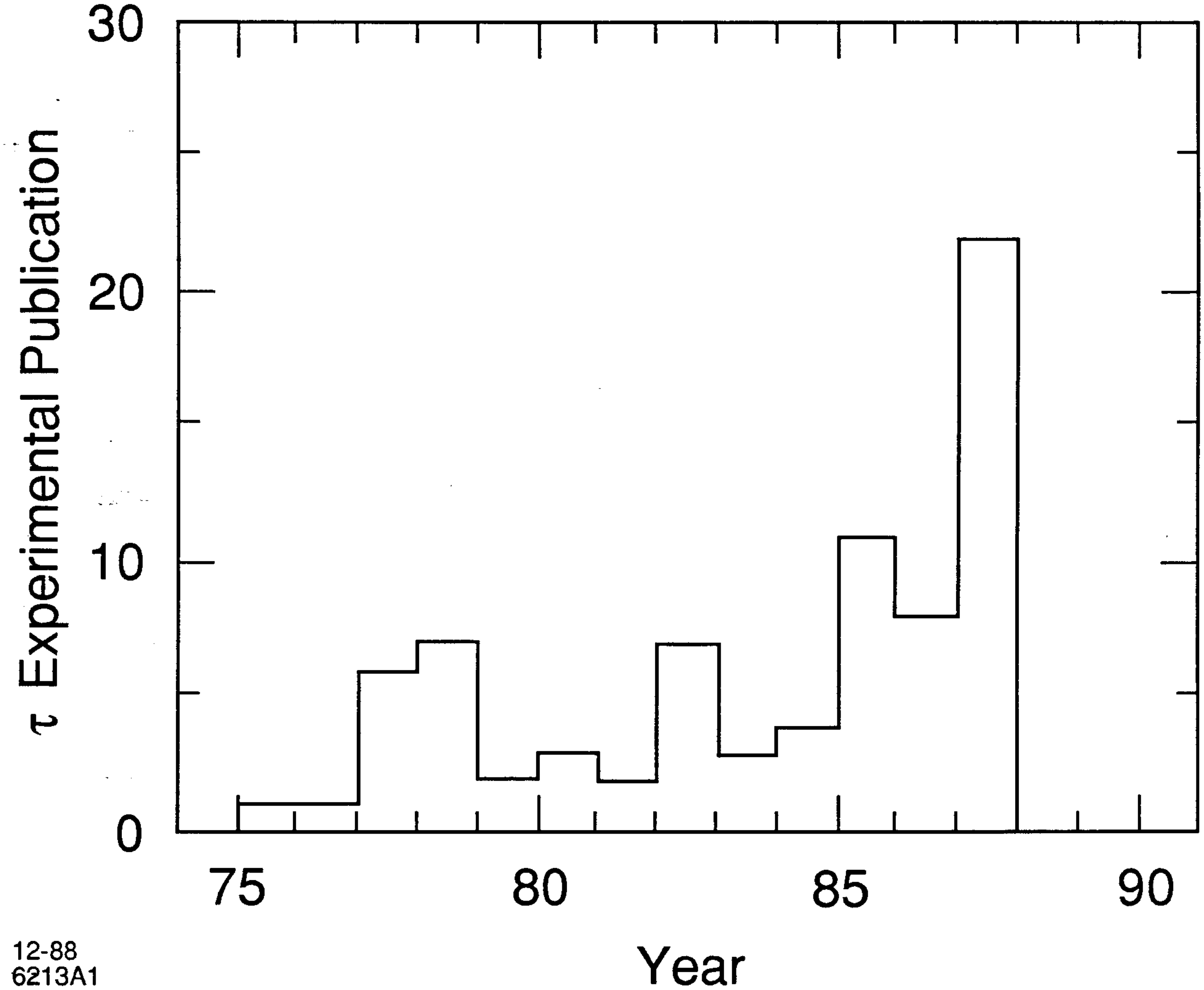

Fig. 1. Published experimental papers on the τ per year.

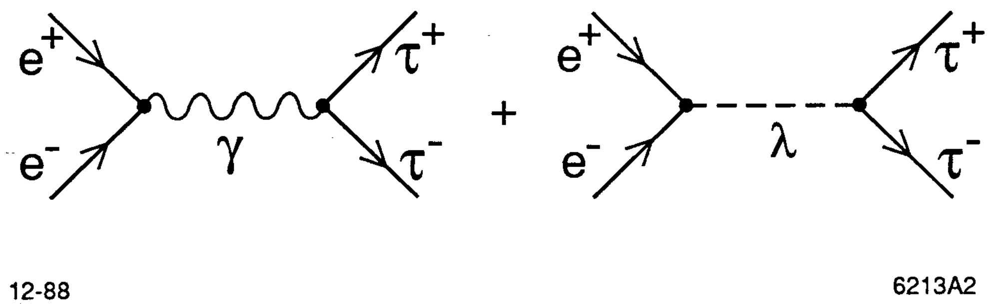

Fig. 2. Feynman diagrams for $e^+e^- \rightarrow \tau^+\tau^-$ if the hypothetical λ particle couples to the e and τ.

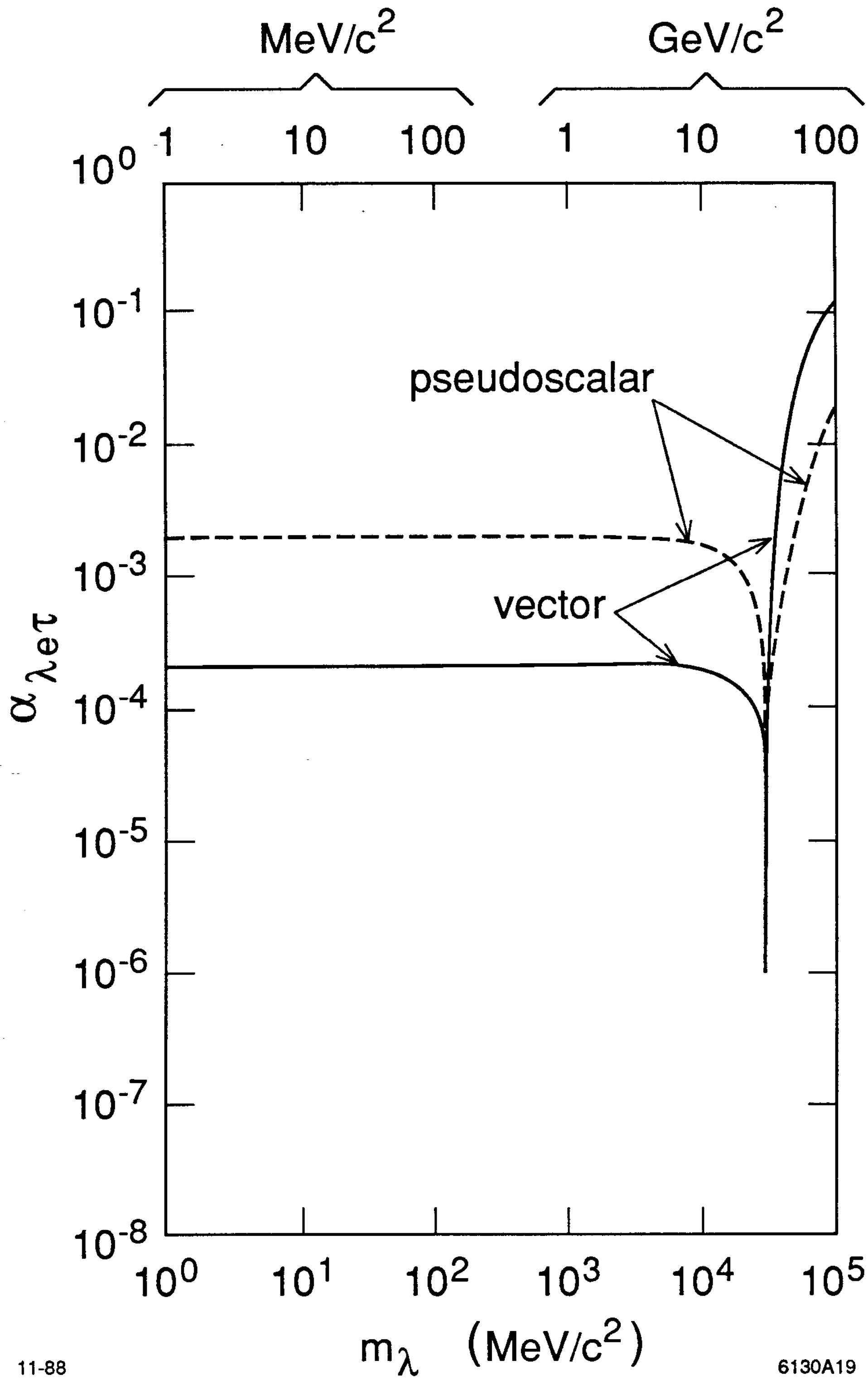

Fig. 3. The curves marked pseudoscalar and vector give the upper limit on $\alpha_{\lambda e\tau}$ from $e^+e^- \to \tau^+\tau^-$ for λ pseudoscalar and λ vector.

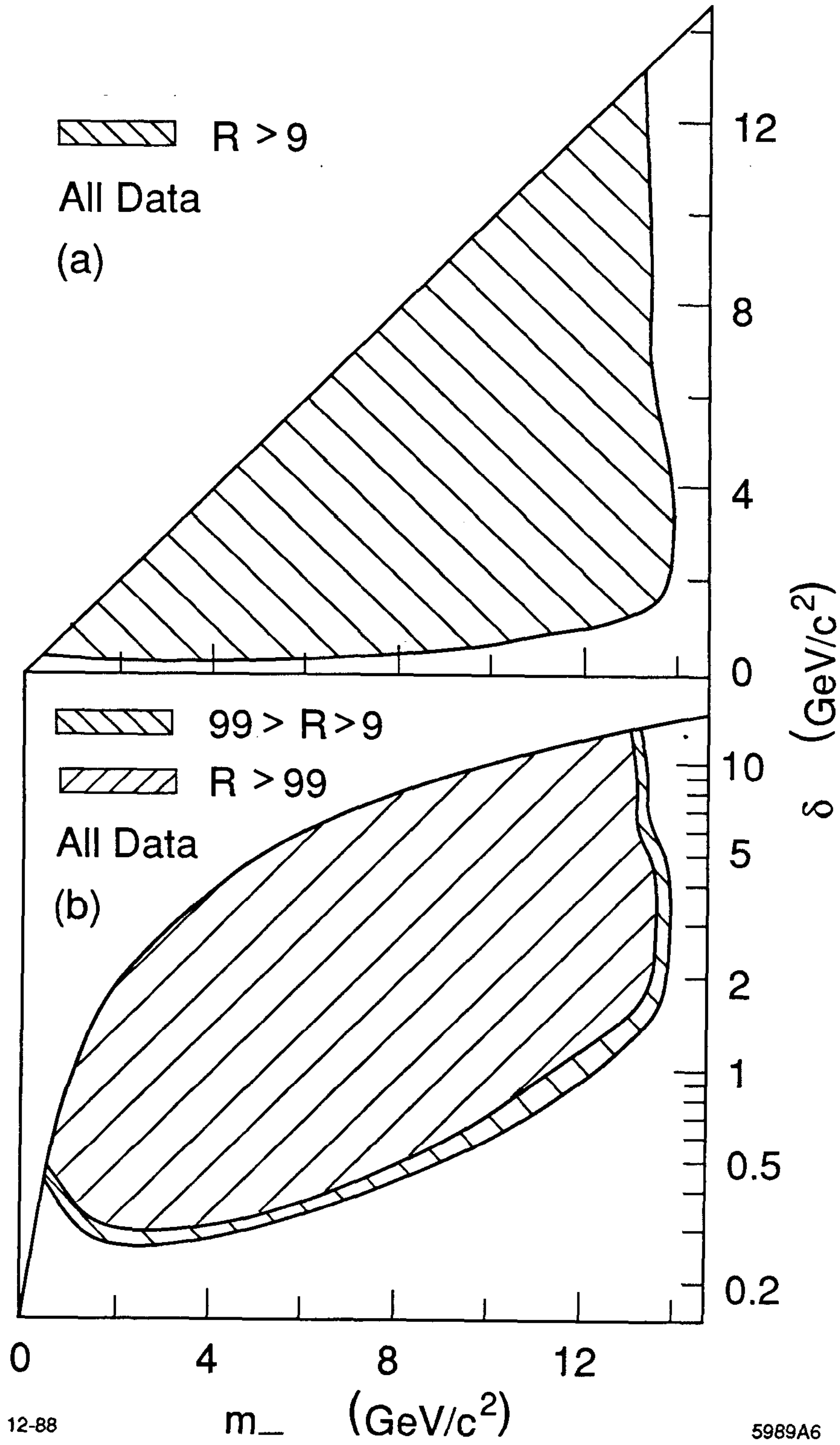

Fig. 4. L^-L^0 pairs are excluded from the hatched $m_- - \delta$ region using 29 GeV e^+e^- data from the Mark II experiment at PEP, Ref. 40. $\delta = m_- - m_0$. The same results are shown (a) with a linear δ scale and (b) with a logarithmic δ scale. $R > 9$ means about 90% C.L.

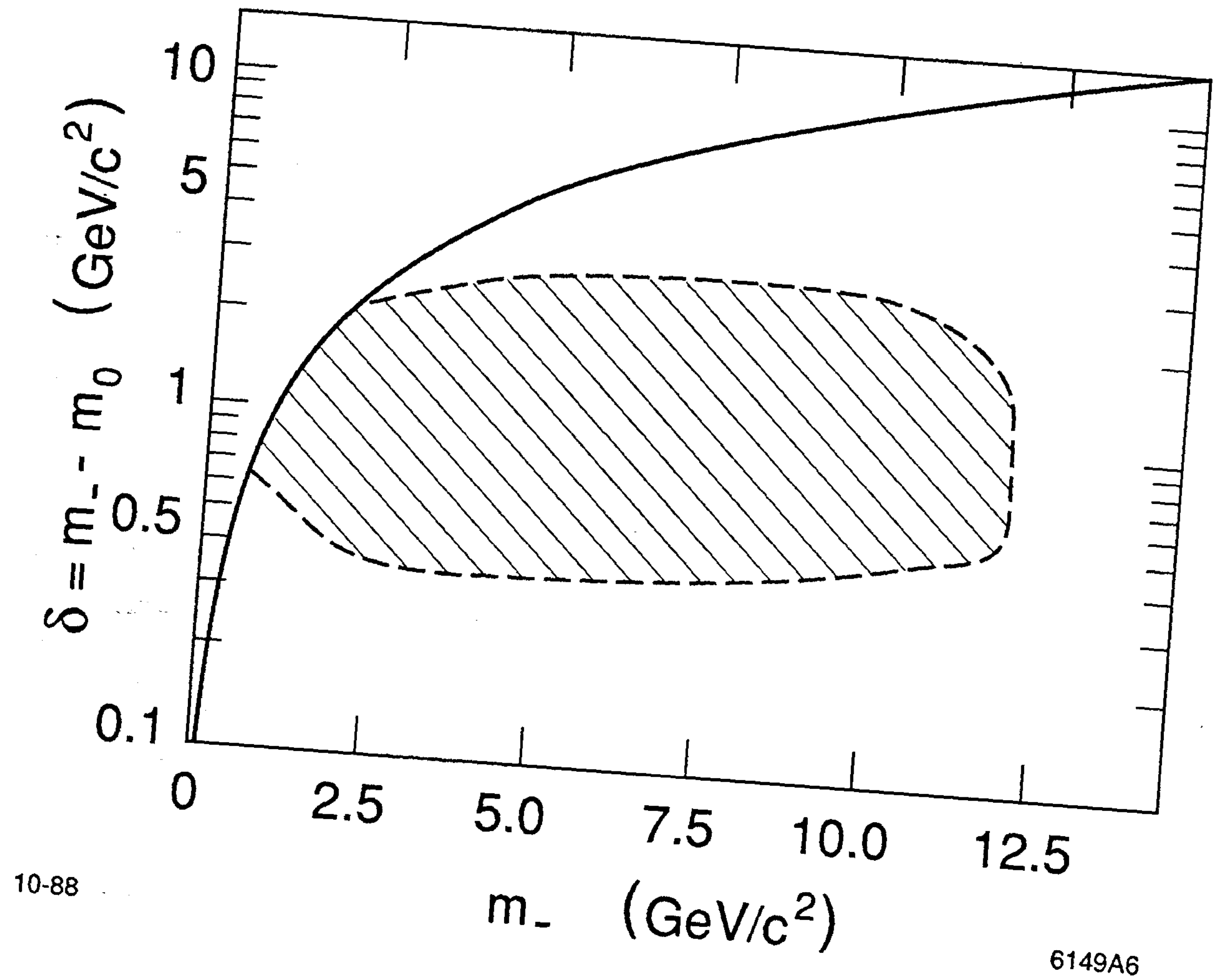

Fig. 5. $L^- - L^0$ pairs are excluded from the hatched $m_- - \delta$ region using 29 GeV e^+e^- data from the TPC experiment at PEP, Ref. 44. $\delta = m_- - m_0$. The boundary gives the 99% C.L.

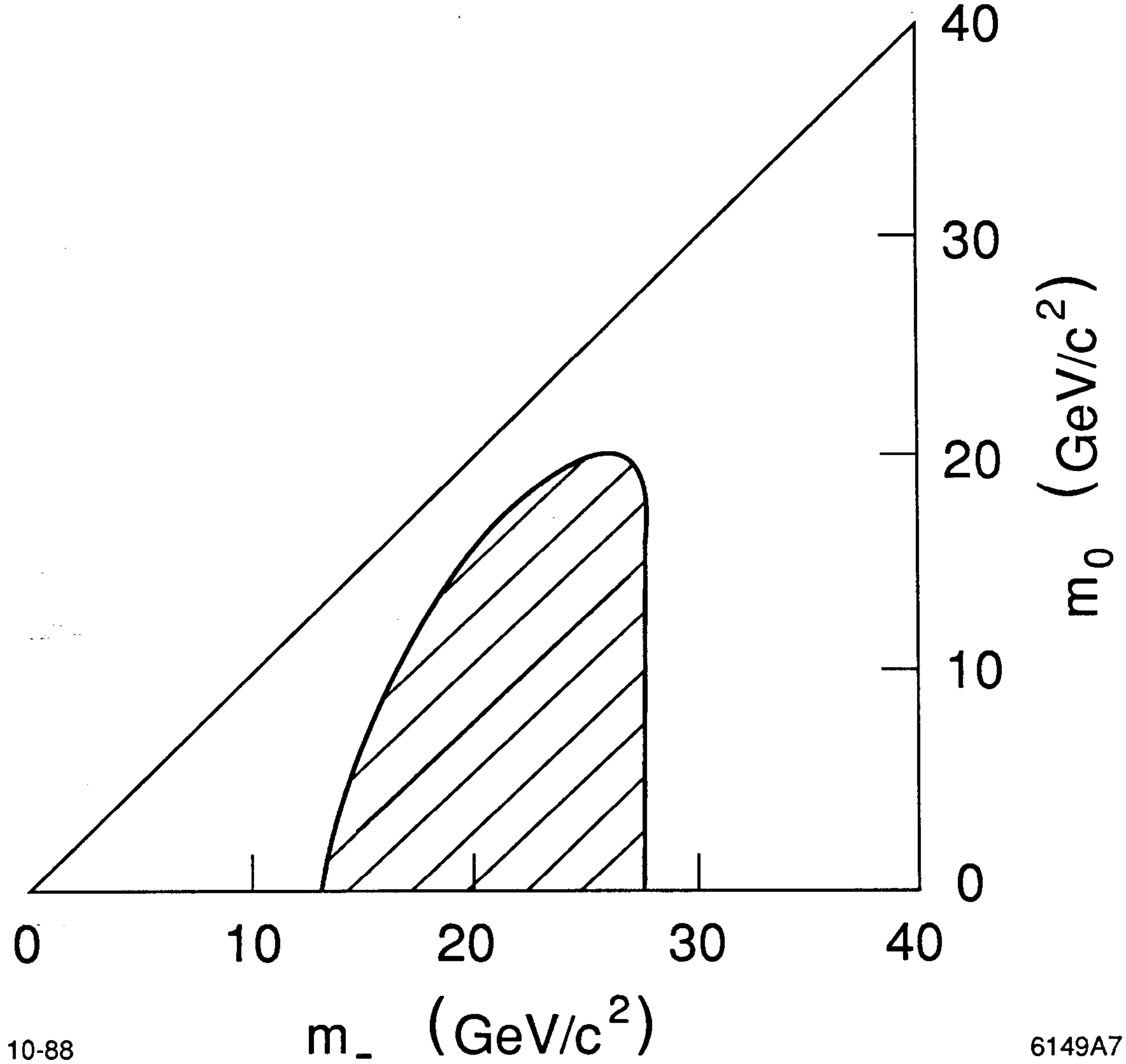

Fig. 6. L^-L^0 pairs are excluded from the hatched $m_- - \delta$ region using 56 GeV e^+e^- data from the AMY experiment at TRISTAN, Ref. 36. The boundary gives the 95% C.L.

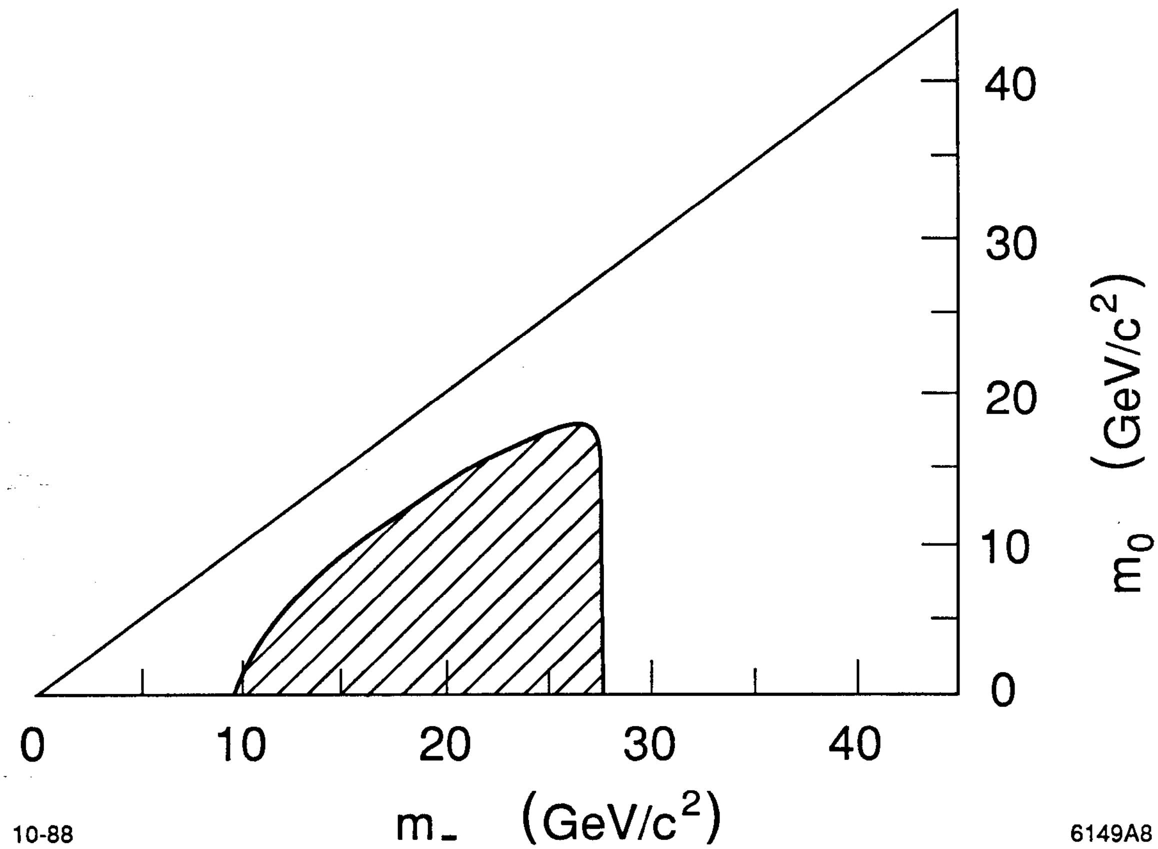

Fig. 7. $L^- - L^0$ pairs are excluded from the hatched $m_- - \delta$ region using 56 GeV e^+e^- data from the VENUS experiment at TRISTAN, Ref. 37. The boundary gives the 95% C.L.

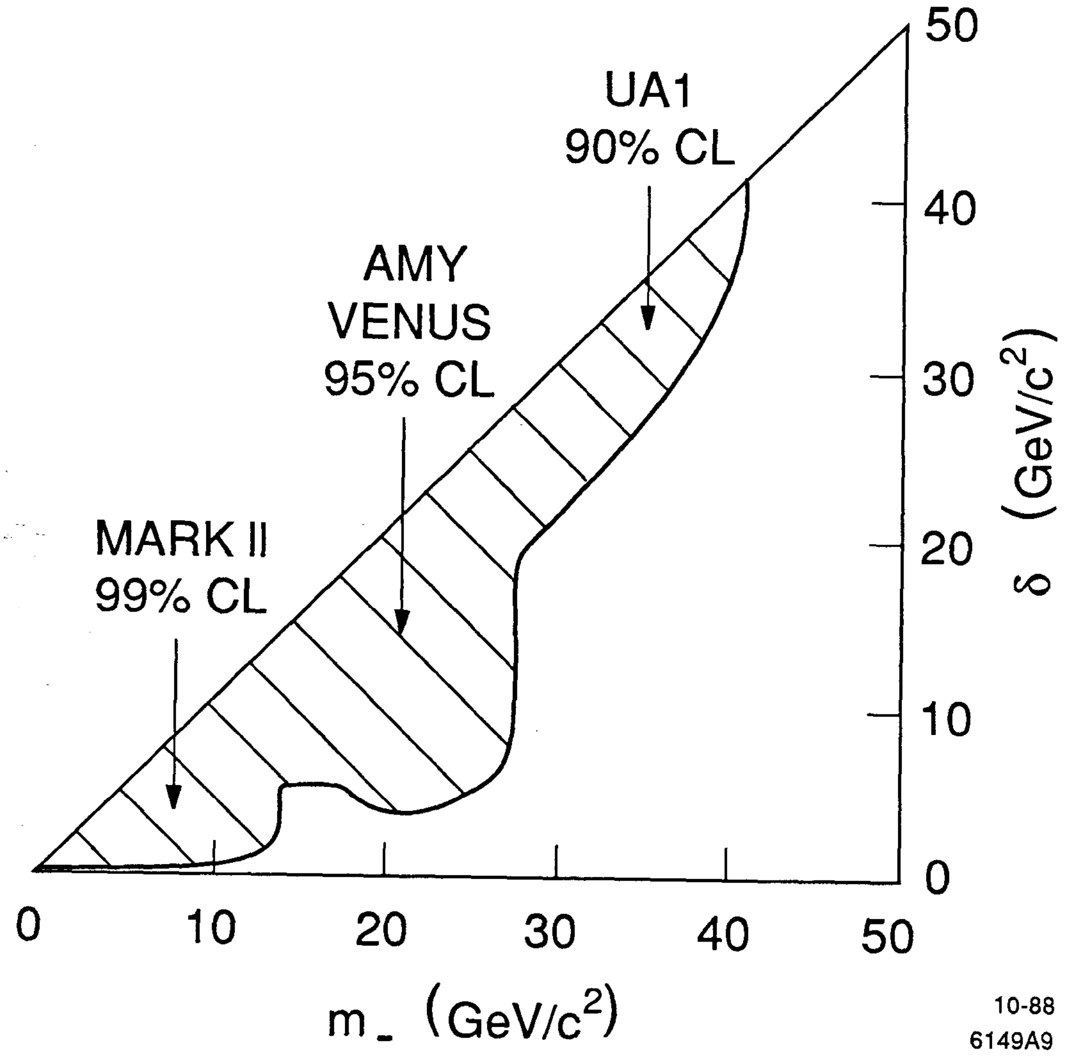

Fig. 8. Composite of $\bar{L} - L^0$ pairs excluded from the hatched $m_- - \delta$ region for: Mark II, Ref. 40, AMY, Ref. 36, VENUS, Ref. 37, UA1, Refs. 42 and 43.